McKinsey Global Institute

Climate risk and response: Physical hazards and socioeconomic impacts

Can coastal cities turn the tide on rising flood risk?

Case study
April 2020

McKinsey Global Institute

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Introduction to case studies

In January 2020, the McKinsey Global Institute published *Climate risk and response: Physical hazards and socioeconomic impacts*. In that report, we measured the impact of climate change by the extent to which it could affect human beings, human-made physical assets, and the natural world. In order to link physical climate risk to socioeconomic impact, we investigated nine specific cases that illustrated exposure to climate change extremes and proximity to physical thresholds. We explored risks today and over the next three decades and examined specific cases to understand the mechanisms through which climate change leads to increased socioeconomic risk. This is one of our case studies, focused on city inundation.

We investigated cases that cover a range of sectors and geographies and provide the basis of a "micro-to-macro" approach that is a characteristic of McKinsey Global Institute research. To inform our selection of cases, we considered over 30 potential combinations of climate hazards, sectors, and geographies based on a review of the literature and expert interviews on the potential direct impacts of physical climate hazards. We found these hazards affect five different key socioeconomic systems: livability and workability, food systems, physical assets, infrastructure services, and natural capital.

We ultimately chose nine cases to reflect these systems and based on their exposure to the extremes of climate change and their proximity today to key physiological, human-made, and ecological thresholds (Exhibit 1). As such, these cases represent leading-edge examples of climate change risk. Each case is specific to a geography and an exposed system, and thus is not representative of an "average" environment or level of risk across the world. Our cases show that the direct risk from climate hazards is determined by the severity of the hazard and its likelihood, the exposure of various "stocks" of capital (people, physical capital, and natural capital) to these hazards, and the resilience of these stocks to the hazards (for example, the ability of physical assets to withstand flooding). We typically define the climate state today as the average conditions between 1998 and 2017, in 2030 as the average between 2021 and 2040, and in 2050 between 2041 and 2060. Through our case studies, we also assess the knock-on effects that could occur, for example to downstream sectors or consumers. We primarily rely on past examples and empirical estimates for this assessment of knock-on effects, which is likely not exhaustive given the complexities associated with socioeconomic systems. Through this "micro" approach, we offer decision makers a methodology by which to assess direct physical climate risk, its characteristics, and its potential knock-on impacts.

Climate science makes extensive use of scenarios ranging from lower (Representative Concentration Pathway 2.6) to higher (RCP 8.5) CO_2 concentrations. We have chosen to focus on RCP 8.5, because the higher-emission scenario it portrays enables us to assess physical risk in the absence of further decarbonization. Such an "inherent risk" assessment allows us to understand the magnitude of the challenge and highlight the case for action. (We also choose a sea level rise scenario for one of our cases that is consistent with the RCP 8.5 trajectory). Our case studies cover each of the five systems we assess to be directly affected by physical climate risk, across geographies and sectors. While climate change will have an economic impact across many sectors, our cases highlight the impact on construction, agriculture, finance, fishing, tourism, manufacturing, real estate, and a range of infrastructure-based sectors. The cases include the following:

— For livability and workability, we look at the risk of exposure to extreme heat and humidity in India and what that could mean for that country's urban population and outdoor-based sectors, as well as at the changing Mediterranean climate and how that could affect sectors such as wine and tourism.

— For food systems, we focus on the likelihood of a multiple-breadbasket failure affecting wheat, corn, rice, and soy, as well as, specifically in Africa, the impact on wheat and coffee production in Ethiopia and cotton and corn production in Mozambique.

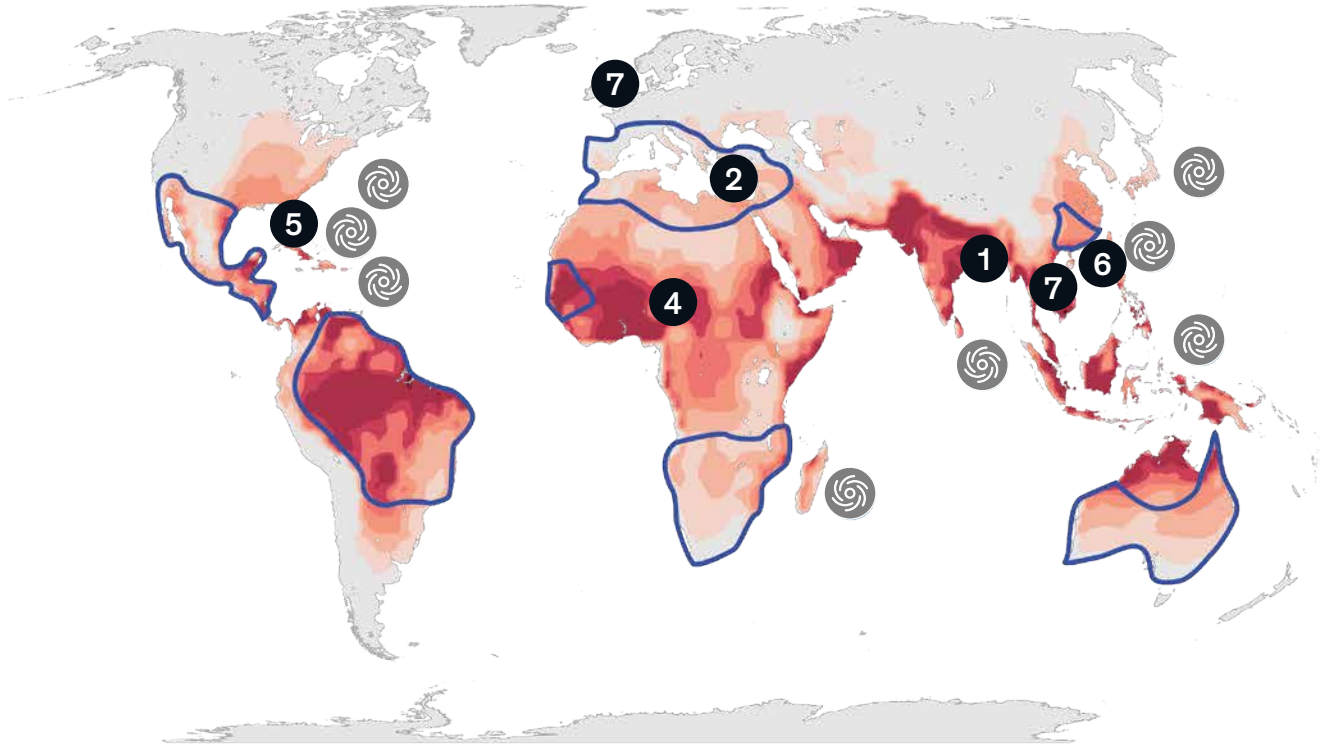
— For physical assets, we look at the potential impact of storm surge and tidal flooding on Florida real estate and the extent to which global supply chains, including for semiconductors and rare earths, could be vulnerable to the changing climate.

— For infrastructure services, we examine 17 types of infrastructure assets, including the potential impact on coastal cities such as Bristol in England and Ho Chi Minh City in Vietnam.

— Finally, for natural capital, we examine the potential impacts of glacial melt and runoff in the Hindu Kush region of the Himalayas; what ocean warming and acidification could mean for global fishing and the people whose livelihoods depend on it; as well as potential disturbance to forests, which cover nearly one-third of the world's land and are key to the way of life for 2.4 billion people.

Exhibit 1

We have selected nine case studies of leading-edge climate change impacts across all major geographies, sectors, and affected systems.



Livability and workability	1	Will India get too hot to work?
	2	A Mediterranean basin without a Mediterranean climate?
Food systems	3	Will the world's breadbaskets become less reliable?
	4	How will African farmers adjust to changing patterns of precipitation?
Physical assets	5	Will mortgages and markets stay afloat in Florida?
	6	Could climate become the weak link in your supply chain?
Infrastructure services	7	Can coastal cities turn the tide on rising flood risk?
	8	Will infrastructure bend or break under climate stress?
Natural capital	9	Reduced dividends on natural capital?

1. Heat stress measured in wet-bulb temperatures.
2. Drought risk defined based on time in drought according to Palmer Drought Severity index (PDSI).

Source: Woods Hole Research Center; McKinsey Global Institute analysis

A family rides a motorbike through flooded streets after a rainstorm in Ho Chi Minh City.
© Sean Gallagher/Getty Images

City inundation

Can coastal cities turn the tide on rising flood risk?

Climate change is increasing the destructive power of flooding from extreme rain and from rising seas and rivers. Many cities around the world are exposed. Strong winds during storms and hurricanes can drive coastal flooding through storm surge. As hurricanes and storms become more severe, surge height increases. Changing hurricane paths may shift risk to new areas. Sea-level rise amplifies storm surge and brings in additional chronic threats of tidal flooding. Pluvial and riverine flooding becomes more severe with increases in heavy precipitation. Floods of different types can combine to create more severe events known as compound flooding. With warming of 1.5 degrees Celsius, 11 percent of the global land area is projected to experience a significant increase in flooding, while warming of 2.0 degrees almost doubles the area at risk.[1]

Urban areas in coastal and riverine environments are on the front line of flooding, and development in these areas is increasing the world's exposure to the risk. These locations have favorable characteristics for urbanization: adjacency to seas and rivers facilitate transportation, and flood plains offer sources of fresh water and flat land for rapid development, among other benefits. At the same time, their urban development has been destroying natural surfaces and increasing nonpermeable surfaces like concrete that limit drainage. The ever-increasing demand for land in urban areas encourages development in higher flood risk areas. To make space for this growth, levees are increasingly narrowing rivers, reducing their flow capacity.

The combination of increased hazard and increased exposure will compound physical climate risk. Coastal cities that have historically faced major flood risks, such as Dhaka, Guangzhou, Miami, Mumbai, New Orleans, and New York, will find that more of their population and assets are at risk. Other cities will face a substantial threat of flooding for the first time. In the United States, 90 coastal communities currently battle chronic flooding, and this number is expected to double in 20 years.[2] Qingdao, China, is projected to experience a 2,000 percent increase in exposure by 2070.[3] Many major African cities, including Lagos, Luanda, and Mogadishu, will also experience a step change in risk.

When cities flood, in addition to often devastating human costs, real estate is destroyed, infrastructure systems fail, and entire populations can be left without critical services such as power, transportation, and communications. For example, during Hurricane Sandy in 2012, up to eight million homes lost electricity.[4] During Hurricane Harvey in 2017, $10 billion of infrastructure was damaged, and most casualties were people attempting to use transportation systems.[5] During Hurricane Irma in 2017, up to 95 percent of cell phone towers were destroyed on some Caribbean islands.[6] Infrastructure systems often serve a population larger than that of the corresponding city. The increasing severity of extreme floods can complicate recovery and repair, affecting populations reliant on these services for longer durations.

1 Petra Döll et al., "Risks for the global freshwater system at 1.5°C and 2°C global warming," *Environmental Research Letters*, April 2018, Volume 13, Number 4.
2 Laura Parker, "Sea level rise will flood hundreds of cities in the near future," *National Geographic*, July 12, 2017.
3 Susan Hanson et al., "A global ranking of port cities with high exposure to climate extremes," *Climatic Change*, January 2011, Volume 104, Number 1.
4 David Sheppard and Scott DiSavino, "Superstorm Sandy cuts power to 8.1 million homes," Reuters, October 30, 2012.
5 "Hurricane Harvey: Most fatalities occurred outside flood zones, Dutch-Texan research shows," European Geosciences Union, April 2018; Collin Eaton, "Hurricane Harvey's damage to Texas infrastructure estimated at $10 billion," *Houston Chronicle*, September 1, 2017.
6 GSMA, *The 2017 Atlantic hurricane season: Mobile industry impact and response in the Caribbean*, March 2018.

Whether cities are disrupted or devastated comes down to small differences in their location, layout, and adaptation. In our case study, we simulate floods at the most granular level (up to two-by-two-meter resolution) and explore how flood risk may evolve for Ho Chi Minh City in Vietnam and Bristol in the United Kingdom (see Box, "Our methodology"). Our aim is to illustrate the changing extent of flooding, the landscape of human exposure, and the magnitude of societal and economic impacts.

We chose these cities for the contrasting perspectives they offer: Ho Chi Minh City in an emerging economy, Bristol in a mature economy; Ho Chi Minh City in a historic flood area, Bristol in an area developing a significant flood risk for the first time. Each city suffers in different ways, but both may experience a step change in threat over the next 30 to 40 years and need to take adaptive action.

The metropolis of Ho Chi Minh City can survive its flood risk today, but its plans for rapid infrastructure expansion and continued economic growth could, if not managed carefully, lead to an increase in risk. The city has a wide range of adaptation options at its disposal but no silver bullet.

In the much smaller city of Bristol, we see a risk of flood damages growing from millions to billions of dollars, driven by high levels of exposure. The city has fewer adaptation options at its disposal, and its biggest challenge may be building political and financial support for change.

Ho Chi Minh City will need to boost adaptation spending to cope with nonlinear flood risk

Ho Chi Minh City is a defining feature of the Vietnamese growth story, contributing approximately a quarter of the country's total GDP. The metropolis is home to eight to nine million people, plus an estimated two million migrant workers.[7] The World Economic Forum describes the country's economy as a "miracle of growth"; it has expanded 6 to 7 percent a year over the past decade.[8] By several estimates, Vietnam could average 5 percent growth a year over the next 30 years.[9] By 2050, this would make Vietnam the 20th-largest economy in the world, ahead of Canada, Italy, and Spain.

To fuel this growth, Ho Chi Minh City is expected to dramatically expand infrastructure systems. Electricity use is expected to nearly triple from 2015 to 2030.[10] On average, at least ~100,000 more people may require housing each year between now and 2050, and access to running water and electricity will be necessary.[11] About 200 infrastructure point assets are currently being planned for construction by 2050.[12] These projects span a diverse range of services needed to meet the needs of a growing and prospering population, including a new metro system, four power plants, nine wastewater processing plants, three water processing plants, four port developments, five data centers, and a new airport. Further expansion is likely planned in roads, electrical transmission infrastructure, and other "continuous" assets for which spatial data are not readily available. Vietnam has already undergone a major infrastructure revolution. In 2016, 99 percent of the Vietnamese population used electricity as its main source of lighting, up from 14 percent in 1993 while rural access to clean water improved over the same period from 17 percent to 70 percent.[13]

7 Ho Chi Minh City Adaptation to Climate Change Volume 2: Main Study Report
8 Peter Vanham, "The story of Viet Nam's economic miracle," World Economic Forum, 2018.
9 John Hawksworth, Hannah Audino, and Rob Clarry, *The world in 2050: The long view: How will the global economic order change by 2050?*, PwC, February 2017.
10 Khanh Vu, "Vietnam will face severe power shortages from 2021: ministry," Reuters, July 31, 2019.
11 UN Development Programme, *Migration, resettlement and climate change in Viet Nam*, April 14, 2014.;City population 2050, Ontario Tech University
12 We define point assets as individual infrastructure items such as power stations, train stations, and water treatment plants, distinct from continuous infrastructure assets such as roads, transmission lines, and railroad tracks.
13 "The World Bank in Vietnam," World Bank.

Box
Our methodology

In our analysis, we use hydrological simulations, land use maps of real estate, infrastructure databases, and damage curves to examine the expected impact of flooding on Ho Chi Minh City and Bristol.[1] We particularly focus on infrastructure due to the knock-on effects associated with its outage. Our analysis selects flood events appropriate to a city's risk (for example, extreme "acute" floods or regular "chronic" floods) and time periods appropriate to each city's development trajectory. In each case study, we follow the same process:

1. We first define a flood of a given recurrence interval (for example, a "100-year" flood, with the equivalent of 1 percent annual probability).

2. We then explore what that flood might look like in different years based on forecasts of the evolution of flood risk in each city. We discuss this from three perspectives: visually, in a high-resolution flood map, at least ten-meter-by-ten-meter; financially, from direct damage to infrastructure and real estate; and economically, from the associated knock-on effects.[2]

3. For Ho Chi Minh City, we add a step and review the impacts of regular flooding at a city-wide level.

4. We then discuss different adaptation options that cities may consider.

These simulations reflect flood defenses as they stand today and do not model future adaptation measures. Furthermore, infrastructure standards and real estate development plans are considered only in relation to best predictions up to about five years in the future. Even if adaptation measures are being planned today, when and how they will manifest is uncertain. In addition, flood simulations considering these measures are not readily available. It is likely that both cities will take some form of adaptation investments over the next 30 years. Therefore, these simulations should be considered perspectives on the value at stake or the inherent risk from inaction rather than predictions of the future.

Additionally, significant uncertainty surrounds flood simulations, particularly in the degree of redundancy in systems, variations in asset-specific flood tolerance, and unpredictability in recovery timelines. Knock-on effects are particularly unclear because they rely on the duration of impact, which shows significant historic variation, and the GDP production associated with very specific areas, which is rarely recorded. However, we find stark difference in impacts between the same severity of flood in different time periods (for example, a 0.5 percent probability flood in Bristol in 2065 would have 17 times greater damage and 22 times greater knock-on effects than a 0.5 percent probability flood today). We believe this provides insight into the magnitude of flood risk increase for each city.

We are grateful for the collaborators who have provided data and detailed review of our flood simulation, including Bristol City Council, Asian Development Bank, Viet Nam National University of Ho Chi Minh, and the Vrije Universiteit Amsterdam. Our Ho Chi Minh City case analysis had significant input from the research team involved in Scussolini et al. (2017).[3] In addition, we would like to thank Arup for providing a detailed peer review of the methodological approach.

1 Our simulation methodology was peer reviewed by engineering consultancy Arup.

2 If not indicated differently, we follow standard practice and define current and future (2030, 2050) states as average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060. 2065 is taken as an instantaneous point in time. Also, if not indicated differently, the climatological analyses in this case use RCP 8.5 to represent the changes in atmospheric greenhouse gas concentrations that could occur under absent a mitigation response. Please see technical appendix of the full report for details.

3 Paolo Scussolini et al., "Adaptation to sea level rise: A multidisciplinary analysis for Ho Chi Minh City, Vietnam." *Water Resources Research,* 2017, Volume 53, Number 12, pp. 10841–57.

Flooding is a common part of life in Ho Chi Minh City. This includes flooding from monsoonal rains, which account for about 90 percent of annual rainfall, tidal floods and storm surge from typhoons and other weather events.[14] Different sources can combine to create more powerful floods.[15] Forty to 45 percent of land in the city is less than one meter above sea level, which, combined with concentrated annual rainfall, results in extensive and frequent flooding. Of the city's 322 communes and wards, 154 have a history of regular flooding.[16] However, while flooding has historically caused property damage, threatened safety, and disrupted transportation, it has not been severe enough to prevent the city from achieving high rates of economic growth.

Rapid urbanization is raising the risk and intensity of floods. The city is already showing evidence of a heat island effect, which may influence precipitation.[17] Between the decade from 1997 and 2006, Ho Chi Minh City's average temperature increased 0.34 degree, compared with an increase of 0.16 degree in the wider Mekong Delta region; this difference is expected to widen as urbanization continues.[18] Urbanization further brings a reduction in permeable surfaces and increases the risk of land subsidence due to building, which has already been observed in the Mekong Delta region and could be as much as three times as significant in terms of flood risk increase as sea-level rise.[19] A major driver of increased flood severity of a given return period is sea-level rise, which contributes to exacerbated storm surges. Precipitation increases could further worsen pluvial and riverine flooding, but there is no clear consensus on where in Vietnam precipitation will change or by how much. Extremes of either supply or shortage are, however, expected to become more common.

Economic growth is also causing land use changes that increase exposure to flooding. The central parts of the city, typically safer due to natural elevation, are "hollowing out" as the growth of commercial and high-end residential real estate pushes people toward more affordable regions on lower ground. Migrants and poorer populations, with the least economic power, are increasingly finding housing in higher flood risk areas. Ho Chi Minh City is already a destination for climate change migrants, particularly rural agricultural victims of flood fleeing to start a new life in the metropolis.[20] As the effects of climate change continue to lead to flooding on Vietnam's coast over the next several decades, migrant populations are likely to increase. These migrants may in fact be re-exposing themselves to risk.

In our analysis, we quantify the possible impact on the city as floods hit real estate and infrastructure assets.[21] Infrastructure assets covered include both those currently available and those under construction, planned, or speculated. Knock-on effects are adjusted for estimates of economic and population growth.[22] We simulate 1 percent probability flooding scenarios for the city for three periods: today, 2050, and a longer-term worst-case scenario of 180 centimeters of sea-level rise. While the third scenario is not predicted in the next

14 Tran, Thong Nhat. "Improvement of flood risk assessment under climate change in Ho Chi Minh City with GIS applications," 2014.

15 Nguyen Ba Thuy et al "Monsoon-induced surge during high tides at the southeast coast of Vietnam: A numerical modelling study," *Geosciences*, 2019, Volume 9, Number 2.

16 HCMC Adaptation to Climate Change Study Report –Volume 2: Main Report -Final Report, Asian Development Bank in collaboration with the HCMC Peoples Committee and DONRE Prepared by ICEM –International Centre for Environmental Management, 31 July 2009.

17 Asian Development Bank, "Ho Chi Minh City adaptation to climate change," 2009.

18 HCMC Adaptation to Climate Change Study Report, Asian Development Bank in collaboration with the HCMC Peoples Committee and DONRE, Prepared by ICEM –International Centre for Environmental Management, 31 July 2009.

19 Hiroshi Takagi, Nguyen Danh Thao, and Le Tuan Anh, "Sea-level rise and land subsidence: Impacts on flood projections for the Mekong Delta's largest city," *Sustainability*, September 2016, Volume 8, Number 9; and Dinh Ho Tong Minh et al, "Mapping ground subsidence phenomena in Ho Chi Minh City through the radar interferometry technique using ALOS PALSAR data," Remote Sensing, 2015, Volume 7, Issue 7.

20 *Adapting to climate change through migration: A case study of the Vietnamese Mekong River Delta,* International Organization for Migration, 2015.

21 Flood modeling and expert guidance were provided by an academic consortium of Institute for Environmental Studies, Vrije Universiteit Amsterdam, and Center of Water Management and Climate Change, Viet Nam National University.

22 In the hydrological model, the main driver of increased flood severity of a given return period is sea-level rise, which manifests itself in exacerbated storm surges. In the absence of a clear consensus on how precipitation may change, fluvial and pluvial flood elements have been kept constant. Similarly, no allowance has been made for the intensification or changing paths of typhoons in the region due to a lack of academic agreement. Therefore, these maps can be considered a conservative view.

30 years, it is possible that some infrastructure with a long design life planned today and built by 2050 may experience this as a worst case.

Flood maps represent events combining riverine and pluvial floods and flooding from sea level extremes (be they tidal or storm surge). We have kept river-based and pluvial flood contributions at the same levels as today throughout all future scenarios due to the precipitation uncertainties discussed above. Similarly, no allowance has been made for the intensification or changing paths of typhoons in the region (which for now hit the northern areas of Vietnam more than the southern parts that include HCMC) due to a lack of clarity on how these could manifest on a granular level.

We first explore in detail how the intensity of an extreme 100-year flood (with a 1 percent probability per year) might change over time. Second, we look at how regular flooding (with a near 100 percent certainty of happening each year) may affect the city over time.

Ho Chi Minh City's extreme flood risk could increase by 5 to 10 times by 2050

Ho Chi Minh City has only a few major infrastructure assets at risk today (City inundation-1). A 1 percent probability "100-year" flood today would deliver a disruptive but likely manageable impact on Ho Chi Minh City's existing infrastructure. We estimate that 23 percent of the city could flood, and a range of existing assets would be taken offline; infrastructure damage may total $200 million to $300 million. Ports, electricity substations, and a power station may suffer, with the average asset flooded to 0.4 meter. Knock-on effects would be significant and, we estimate, could total a further $100 million to $400 million. Direct inundation would reduce hours worked. If substations do not have additional protection above average levels, up to 20 percent of substations might fail, causing outages. Approximately 15 percent of the water supply could be cut off. Although roads are resistant to damage, they typically become inoperable sooner than other infrastructure elements, and 95 percent of traffic consists of scooters, which have a lower flood threshold than cars. The absence of metro transportation means increased reliance on roads. Most expected damage is instead in real estate, which may total $1.5 billion of damage. Overall, however, the duration of outages, although typically longer than after a comparable flood in more developed countries, may be only a matter of days.

A flood with the same probability in 30 years' time would likely do three times the physical infrastructure damage and deliver 20 times the knock-on effects (City inundation-2). In this scenario, we estimate that 36 percent of the city becomes flooded. Small increases in flood exposure and flood depth would be enough to trip the thresholds of some infrastructure, with the average flooded asset at 0.5 meter. In addition, many of the 200 new infrastructure assets are planned to be built in flooded areas. As a result, the damage bill would grow, totaling $500 million to $1 billion. New, sensitive, and expensive assets such as the city's underground metro stations in the highest-risk areas would be damaged. Damaged assets could include 5 percent of new metro stations, 50 percent of data centers, 10 percent of wastewater facilities, one power station, 30 percent of substations, and a port. Roads would begin to reach damage thresholds, with at least 10 percent requiring repair. About $8.5 billion of damage could also be incurred on real estate as larger areas flood to greater depths.

Increased economic reliance on assets in flooded areas would amplify knock-on effects, leading to an estimated $1.5 billion to $8.5 billion in losses. Widespread disruption to new and existing infrastructure could be expected for weeks. The threat to the metro could close a number of lines, resulting in at least a partial shutdown of the system. Furthermore, with more than 20 percent of elevated metro stations experiencing flooding at depths greater than 0.5 meter, commuters may struggle to use them even if the stations are safe from damage. This disruption may affect around one million daily commuters. Thirty percent of transformers in the city could be affected, possibly leading to an increase in localized blackouts, and damage to wastewater processing plants could cause one million to ten million gallons of sewage overflow into the city. About 15 percent of the water supply is likely to be cut off, and road disruptions would also worsen.

Assets in planning today with long expected lives (such as the metro) could exist long enough to experience a 1 percent probability flood in a 180-centimeter sea-level-rise scenario by the end of the century, if significant action is not taken to mitigate climate change (City inundation-3). If it occurs, a 1 percent probability flood in this scenario may bring three times the extent of flood area and seven times the depth compared with today. About 66 percent of the city would be underwater, driven by a large western area that suddenly passes an elevation threshold. The centre of HCMC would become a temporary island. Affected assets would be flooded to an average depth of 0.9 meters, enough to surpass the typical damage thresholds seen in many historic floods, even for relatively modern constructions.

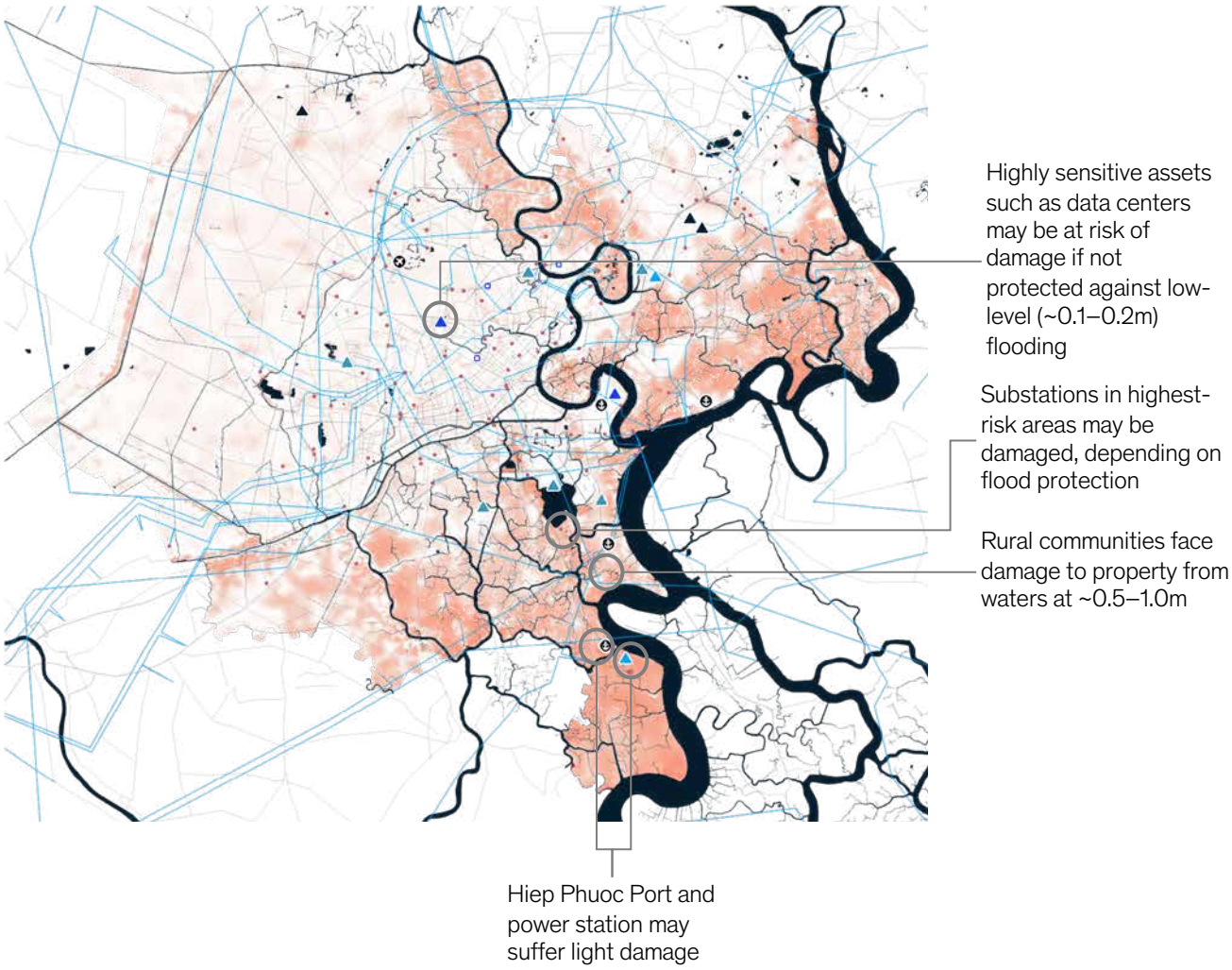
Under this scenario, infrastructure damage is critical and widespread, totaling an estimated $3.8 billion to $7.3 billion. The list of damaged assets would be long: 50 percent of data centers, 50 percent of wastewater processing plants, two power stations, 50 percent of substations, and three ports may all suffer damage. Half of roads would exceed the repair threshold, a quarter of metro stations could be damaged, and as many as 60 percent may be inoperable or inaccessible. Assets flooded in previous scenarios would sustain more severe damage. Real estate damage could total $18 billion. Much of the city's functionality may be shut down, with knock-on effects of $6.4 billion to $45.1 billion. With so many stations inoperable or inaccessible, the metro would almost certainly be shut down, disrupting as many as three million daily commutes. Wastewater plant failures would increase the volume of sewage overflows, potentially spilling two million to 50 million gallons of sewage into the city. The proportion of inoperable substations may approach 50 percent, significantly increasing the risk of a full blackout. If this happens, water supply would likely be cut off to the entire population for the duration. The extent and severity of the flood would likely shut down the city, with impacts possibly lasting a month or more.[23] This scenario is extreme, and the probability of it occurring by 2050 is negligible. What is important, though, is that infrastructure planned for completion in or shortly before 2050 could experience another step change in risk at some point in 2060 or beyond if significant mitigation does not take place (City inundation-4).

[23] We derive sea-level rise of 180 centimeters from a high-end interpretation of RCP 8.5 by the end of the century. It is posed as a worst-case scenario that infrastructure planned today and built by 2050 with a design life of more than 50 years may experience in its lifetime.

Ho Chi Minh City has only a few major infrastructure assets at risk today; most damage would be to real estate.

Based on RCP 8.5

Visualization of depths and extents of 100-year flood today


Highly sensitive assets such as data centers may be at risk of damage if not protected against low-level (~0.1–0.2m) flooding
Substations in highest-risk areas may be damaged, depending on flood protection
Rural communities face damage to property from waters at ~0.5–1.0m
Hiep Phuoc Port and power station may suffer light damage

Infrastructure

Power plant · Waste-water plant · Data center · Water treatment plant · Sub-station · High-voltage transmission line · Train station · Port · Airport

Inundation depth

Meters 0 – 2.8

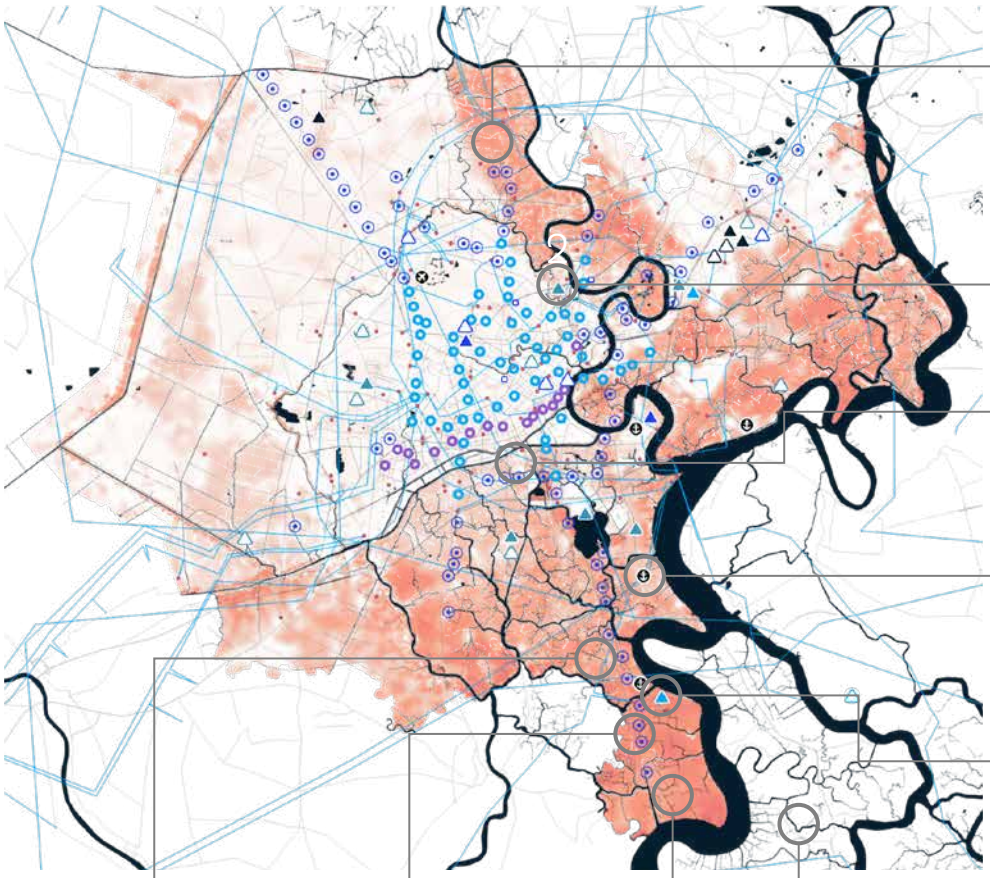
Note: See the Technical Appendix of the full report for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multimodel ensemble. Heat data bias corrected.

Source: National University of Viet Nam; Scussolini et al., 2017; UN; Vietnam Metrological Agency; World Bank; McKinsey Global Institute analysis

Ho Chi Minh City's new infrastructure systems would be at immediate risk from flooding in 2050.

Based on RCP 8.5

Visualization of depths and extents of 100-year flood in 2050[1]



Roads in Vietnam are typically more resistant to floods than those in many developed countries, but 10% sustain damage in this scenario

Tham Luon-Ben Cat wastewater plant—largest in Vietnam—likely overflows

Informal settlement areas in central Ho Chi Minh City that have gradually expanded south are flooded

Multiple major ports are taken offline, representing >85% of Ho Chi Minh City's freight traffic today

Planned expansion of Hiep Phuoc Thermal Power Station—likely to be largest in Vietnam—floods over 1.4m

Nha Be, a historically poor part of Ho Chi Minh City, is flooded

Metro stations on proposed line 4 south may become inaccessible

Flood depths exceed 1.5m in worst-hit parts of city

Can Gio, historically one of the poorest parts of Ho Chi Minh City, is flooded extensively[1]

Infrastructure

Existing: Power plant; Waste-water plant; Data center; Water treatment plant; Sub-station; High-voltage transmission line; Train station; Port; Airport

Planned: Power plant; Waste-water plant; Data center; Water treatment plant; Metro (aboveground); Metro (overground); Metro (underground)

Inundation depth

0 — 2.8

Meters

1. It is not included in this visualization, but other academic papers have modeled severe flood risks for Can Gio.

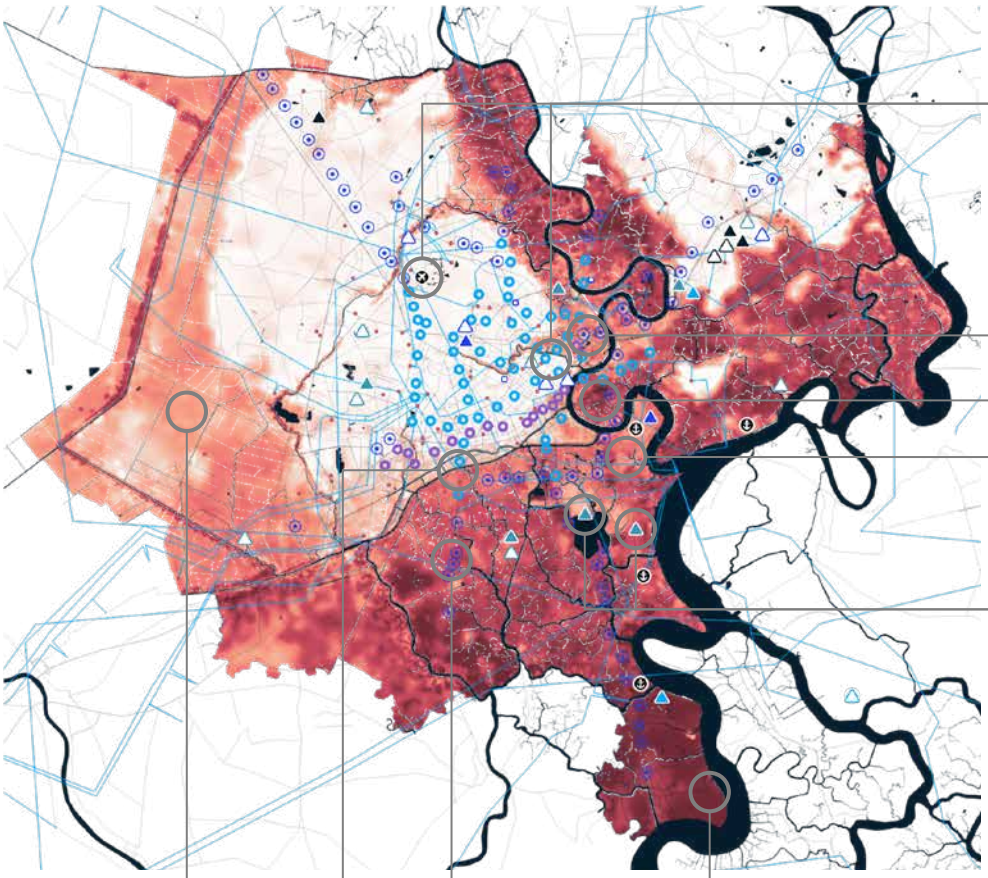
Note: See the Technical Appendix of the full report for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multimodel ensemble. Heat data bias corrected.

Source: National University of Viet Nam; Scussolini et al., 2017; UN; Vietnam Meteorological Agency; World Bank; McKinsey Global Institute analysis

In a scenario of 180cm sea-level rise, deeper and more extensive flooding would flood the majority of Ho Chi Minh City.

Based on RCP 8.5

Visualization of depths and extents of 100-year flood in 180cm sea-level rise scenario[1]



Airport and central business district remain safe due to elevation, but central city is temporarily cut off from surrounding areas

City's tallest building, $1.5 billion Landmark 81, is cut off by flooding

Districts 2 and 7, among city's fastest-growing areas and home of expat community, severely flooded

Bing Hung wastewater plant, earmarked for expansion to become largest wastewater plant in SE Asia, floods

Binh Chanh, a historically poor part of Ho Chi Minh City, flooded extensively

Sensitive underground metro stations flood

Metro stations on proposed line 5 become inaccessible

Flood depths exceed 2.5m in worst-hit parts of city

Infrastructure

Existing: Power plant; Waste-water plant; Data center; Water treatment plant; Sub-station; High-voltage transmission line; Train station; Port; Airport

Planned: Power plant; Waste-water plant; Data center; Water treatment plant; Metro (aboveground); Metro (overground); Metro (underground)

Inundation depth 0 — 2.8

Meters

1. Assets in planning today with long expected design lives (such as the metro) could exist long enough to experience a 1% probability flood in a 180cm sea-level-rise scenario by the end of the century if significant action is not taken to mitigate climate change.

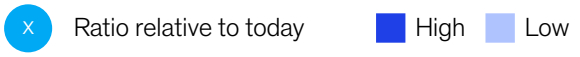
Note: Observations are additional to 2050 scenario. See the Technical Appendix of the full report for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multimodel ensemble. Heat data bias corrected.

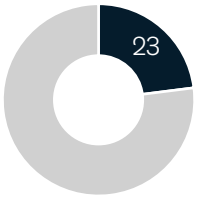
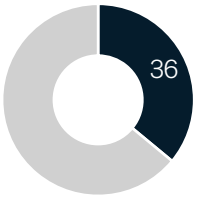
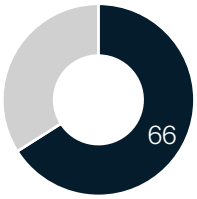
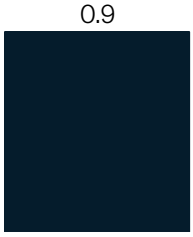
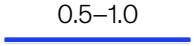
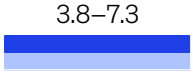
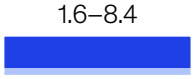
Source: National University of Viet Nam; Scussolini et al., 2017; UN; Vietnam Meteorological Agency; World Bank; McKinsey Global Institute analysis

Ho Chi Minh City could experience 5 to 10 times the economic impact from an extreme flood in 2050 vs today.

Based on RCP 8.5

100-year flood effects in Ho Chi Minh City[1]



		Today	2050	180cm sea-level rise scenario[2]
Flooding	**Flooded area within modeled area** %		 1.5x	 3x
	Average flooded depth within modeled area Meters	0.1	0.3 2x	 0.9 7x
Impacts $ billion	**Real estate damage and destruction**[3]	1.5	8.4 6x	18.0 13x
	Infrastructure damage and destruction[3]	0.2–0.3	 0.5–1.0 3x	 3.8–7.3 22x
		Moderate damage to specific infrastructure, incl substations, data centers, 1 power station	Widespread damage to infrastructure, incl ~5% of metro stations, ports, wastewater treatment	Widespread severe damage, incl ~25% of metro stations, roads, 2 power stations
	Knock-on effects[3]	0.1–0.4	 1.6–8.4 20x	6.4–45.1 104x
		Possible blackouts to ~20% of substations; possible disruption of ~15% of water supply	Partial metro closure affecting ~1 million trips; sewage overflows; possible blackouts to ~30% of substations	Full metro closure affecting ~3 million trips; large sewage overflows; risk of full blackout

1. Repair and replacement costs. Qualitative descriptions of damage and knock-on effects are additional to previous scenarios.
2. Assets in planning today with long expected design lives (such as the metro) could exist long enough to experience a 1% probability flood in a 180-centimeter sea-level-rise worst-case scenario by the end of the century if significant action is not taken to mitigate climate change.
3. Value of wider societal consequences of flooding, with a focus on those attributable to infrastructure failure, includes loss of freight movement, lost data revenues, and lost working hours due to a lack of access to electricity, clean water, and metro services. Adjusted for economic and population growth to 2050 for both 2050 and 180cm sea-level rise scenarios.

Note: See the Technical Appendix of the full report for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Following standard practice, we define future states (current, 2030, 2050) as the average climatic behavior over multidecade periods. The climate state today is defined as the average conditions between 1998–2017, in 2030 as the average between 2021–40, and in 2050 between 2041–60. Assumes no further adaptation action is taken. Figures may not sum to 100% because of rounding.

Source: Asian Development Bank; BTE; CAPRA; CATDAT disaster database; Daniell et al., 2017; Dutch Ministry of Infrastructure and Environment; ECLAC; EU Commission; HAZUS; Oxford Economics; People's Committee of Ho Chi Minh City; Scussolini et al., 2017; UN; Viet Nam National University, Ho Chi Minh City; World Bank; historical insurance data; review of critical points of failure in infrastructure assets by chartered engineering consultants; McKinsey Global Institute analysis

Intensifying regular floods may cost 3 percent of Ho Chi Minh City's GDP annually by 2050

While "tail" events may suddenly break systems and cause extraordinary impact, extreme floods will be infrequent. Intensifying chronic events are more likely to have a greater effect on the economy, with a mounting annual burden over time (City inundation-5). The accumulation of small but more probable impacts will be at best a structural disadvantage to the city or, worse, a barrier to economic growth.

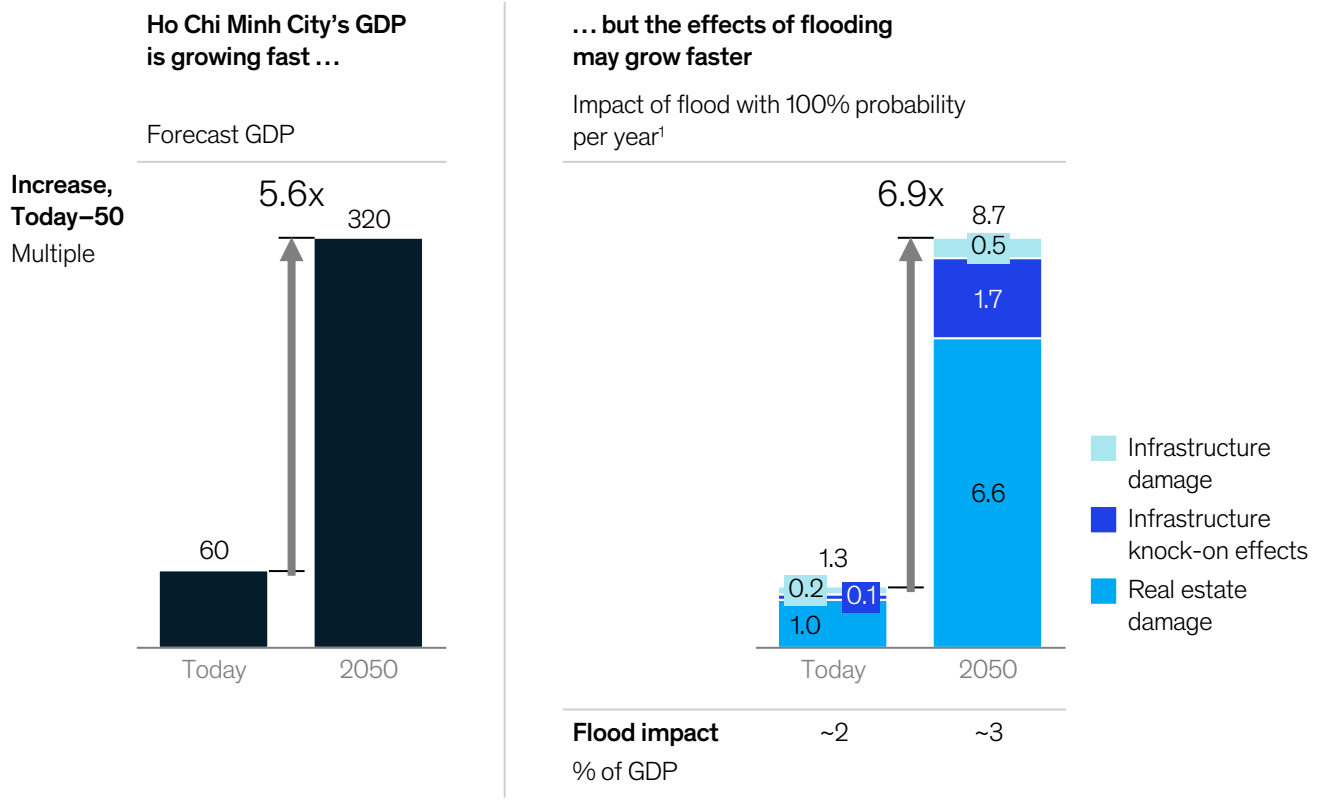
Case study City inundation-5

Without further adaptation, the costs associated with floods expected to occur annually in Ho Chi Minh City may grow faster than GDP.

Based on RCP 8.5

GDP and cost impact

2019 $ billion



1. A flood with 100% probability per year can be considered a flood with a 1-year return period—a level of flooding that can be considered with near certainty to be the minimum that will be observed in a year.

Note: See the Technical Appendix of the full report for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multimodel ensemble. Heat data bias corrected. Assumes no further adaptation action is taken. Not to scale. Figures may not sum to 100% because of rounding.

Source: Asian Development Bank; BTE; CAPRA; CATDAT disaster database; Daniell et al., 2017; Dutch Ministry of Infrastructure and Environment; ECLAC; EU Commission; HAZUS; Oxford Economics; People's Committee of Ho Chi Minh City; Scussolini et al., 2017; UN; Viet Nam National University, Ho Chi Minh City; World Bank; historical insurance data; review of critical points of failure in infrastructure assets by chartered engineering consultants; McKinsey Global Institute analysis

Today, annual flooding could be compared to a tax on the economy. Using the flood maps and assumptions described, annual flood impacts may amount to about $1.3 billion a year, predominantly from real estate damage. This represents approximately 2 percent of the city's GDP. The city has not only survived this for many years, but has continued to grow rapidly. But regular flooding costs will continue to rise, and faster than economic activity. Ho Chi Minh City should expect significant disruptions each year, and regular damage could reach $8.7 billion. While real estate damage is still the largest cost, effects on infrastructure—particularly in the form of knock-on effects—would have an increased contribution as assets such as the metro

become inaccessible for periods of time. Left unchecked, regular flooding could represent an annual cost of 3 percent of GDP by 2050. More critically, the threat to the lives of citizens of the city would also expand, as indicated by the change in flood depths and water volumes, possibly quintupling.[24]

Adaptation measures in Ho Chi Minh City might require total investments comparable to the city's annual GDP today

Ho Chi Minh City is clearly centered on an area of high flood risk. Today, the city lives with this level of flood risk. Tomorrow, however, impacts will grow. If infrastructure development and wider land use policy do not adapt, by 2050 regular flooding will increase costs to the economy, and the threat of an extreme flood could be devastating. The city's extensive infrastructure plans may be at odds with the changing climate that assets experience when built.

Ho Chi Minh City has time to adapt, and other urban areas have overcome worse exposures. With approximately 40 to 45 percent of its land area at one meter or less above sea level, the city is topographically less exposed than the Netherlands, where approximately 50 percent of land sits one meter or less above sea level, with a similar level of urbanization on average. The city has many options to avert impacts because it is still early in its development journey. The city is also already investing considerably against flooding and in 2016 committed to spending a further $4.4 billion in flood defenses over the next five years, particularly for pumping stations and improved drainage systems.[25] Much more will be needed—the bill for Singapore, for example, is estimated at over $72 billion.[26]

In this section we discuss a range of adaptation measures. Each has trade-offs, including coverage, cost, social implications, and ease of implementation. This study does not make a recommendation on which solutions should be pursued, as these have not been extensively modeled; additionally, if certain adaptation measures discussed in this section may be implemented, others may not be necessary anymore; but we encourage stakeholders to consider the relative merits of each. Less than half of the city's major infrastructure needed for 2050 exists today. Many of the potential adaptation options could be highly effective. However, it is unlikely that any single measure will be easy or without disadvantages.

Better planning to reduce exposure and risk

The city's latest master plan is named "The Adjustment Plan" because it takes the original 1998 Urban Master Plan and adjusts for the realities of the unpredictable and largely decentralized economic transformation the city has seen. This growth makes urban planning for lowering flood risk challenging.

Ho Chi Minh City's planned assets are broadly similar in their exposure to current levels of climate risk. For asset types where geographic discretion is possible, new assets may be better positioned than existing infrastructure. Substations built in the past ten years appear 30 to 50 percent less exposed to floods than those that are older. However, relocation of existing infrastructure assets has not yet occurred. While shifting old assets may be prohibitively expensive, several exposed assets are earmarked for substantial upgrades, and plans could be reassessed in light of the latest climate predictions. In real estate, the shifting of homes has already begun, and economic realignment toward a service economy may reduce reliance on larger industrial real estate in more vulnerable areas.

[24] This reflects merely a calculation of physical flooding conditions that can potentially lead to the threat of drowning based on water depths and water velocities as informed by the SUFRI project of the Crue Era-New (Diaz-Loaiza et al., 2012; Jobstl et al., 2011). Because death by flood is a highly complex phenomenon that still eludes realistic representation by algorithms, the results of our casualties estimation should be considered as the statistical number of people that may face life-threatening situations during the flood. While is no reliable form of accurately predicting exact numbers of casualties, relative values can give an indication of increased risk.

[25] "Ho Chi Minh City to spend $4.4bn to keep its head above water", *Global Construction Review*, 30 September 2016.

[26] James Crabtree, "Asia's megacities must learn from Indonesia's capital move," *Nikkei Asian Review*, August 29, 2019

Reducing exposure to flooding entails social and financial trade-offs. Inevitably, the ability to shift some infrastructure away from flooding affects cost and functionality. The metro is an example of the latter—it cannot be moved without changing the population that can use it. Other assets may also incur construction cost increases, such as substations, which may incur increased geotechnical costs at different elevations and a need for longer lengths of transmission cables to connect to the wider system. This leads to a complex financial and political discussion of the benefits of building some of these assets versus the possible costs of their exposure.

Investing in adaptation through hardening and resilience

Asset hardening may need significant investment and is currently being considered in many forms by city leaders. Today defenses are limited, and evidence suggests that poor maintenance hampers the effectiveness of existing dikes and drainage systems.[27] The most discussed approach to new investment is the MARD Plan Variant (a reference to an originally much larger plan) which would create a ring dike around the most developed parts of the city. From an infrastructure perspective, in a location with flooding as severe as that projected for Ho Chi Minh City by 2050, our modeling suggests that this hardening measure would save only certain infrastructure assets at the expense of others, with the average change in flood depths across all assets being approximately zero. The measure may also amplify the impact on the poorest areas of real estate when protecting richer areas. Even this reduced version of the plan would come with a large estimated price tag, about $800 million.[28] Larger systems such as river and tidal barriers may provide better coverage by addressing floods at one of the sources but will come at a much higher cost. The Soài Rap tidal barrier and Go Cong Sea Dyke projects are such approaches; cost estimates are not available, but the projected cost for Jakarta's major coastal defense plans is roughly $40 billion, comparable to Ho Chi Minh City's current GDP.[29]

Natural measures may be the most cost-effective form of hardening. Mangroves currently offer significant protection from more extreme events, reducing the height of storm surge by 20 percent or more for every 100 meters of forest.[30] The city has made substantial achievements in replanting 160 square kilometers in the past 35 years, bucking a trend of a decline of 60 percent in the country over the past 70 years.[31]

A more strategic approach may be to improve resilience, such as by adjusting building codes, but this requires political leadership and infrastructure owner buy-in. Historical evidence suggests that certain types of infrastructure built in the past eight years have demonstrated notably greater resistance to floods than their historic counterparts. The benefits of these improvements are economically significant. If all current and planned power stations in Ho Chi Minh City demonstrated the characteristics of newer variants, approximately $100 million in direct damage might be saved in a 100-year flood in 2050. The benefits from avoided knock-on effects would add to that total, but these are more conditional on the spread of the standard—if one critical part of an infrastructure system fails, functionality can be cut even if all other assets are built to high standards.

While it is possible to assess benefits, understanding the costs of tightening standards is much harder. Research from the Global Commission on Adaptation suggests the best performing infrastructure adaptation methods can achieve cost-benefit ratios of 1:5 to 1:10.[32]

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27 Ho Chi Minh City Flood and Inundation Management. Final report, volume 2: IFRM strategy annex 1: Analysis of flood and inundation hazards, FIM, 2013. Paolo Scussolini et al. "Adaptation to sea level rise: A multidisciplinary analysis for Ho Chi Minh City, Vietnam." *Water Resources Research,* 2017, Volume 53, Number 12, pp. 10841–57.

28 Paolo Scussolini, et al; *Adaptation to sea level rise: A multidisciplinary analysis for Ho Chi Minh City, Vietnam,* Water Resources Research, 53, 2017.

29 Philip Sherwell, "$40bn to save Jakarta: The story of the Great Garuda," *Guardian*, November 22, 2016.

30 Dasgupta, Susmita, et al. "Quantifying the protective capacity of mangroves from storm surges in coastal Bangladesh." PloS one 14.3 (2019): e0214079; Mark Spalding et al; *Mangroves for coastal defence: Guidelines for coastal managers & policy makers,* Wetlands International and The Nature Conservancy, 2014.

31 Eric San Juan, "The evolution of Can Gio—from desert to UNESCO biosphere reserve," *Saigoneer*, March 20, 2014.

32 Manish Bapna et al., *Adapt now: A global call for leadership on climate resilience*, Global Commission on Adaptation, September 2019.

Considering the expected annual damages from exclusively 1 percent and 100 percent flooding events (other events will in practice have impacts), this implies one-off spending of ~$15 billion to $25 billion on adaptation measures, assuming 50 percent of damages can be avoided, damages scaled linearly between years, and no discounting is considered. This method requires effective governance as well as the financial capacity for infrastructure providers to afford higher standards, because owners may foot the bill. If infrastructure creation dries up as a result of tougher standards, negative economic impacts may ensue. For some of the most sensitive assets, such as the metro, options for tighter standards may be limited, and more extreme measures (such as elevation) could be the only option. An estimated extra $2 billion to $7 billion is already earmarked for spending on elevating certain high-risk metro stations.[33] This protects them from damage but does little to keep them operational when their access is flooded.

The possibility of tightening building codes in real estate could give an even greater relative improvement than in infrastructure, due to the very low levels of regulation in some parts of housing stock. Real estate codes can also help reduce exposure to hazard by introducing more permeable surfaces to increase drainage and reduce flood depth. The city has already started to invest in digital solutions to improve the resilience of the electrical grid to day-to-day interruptions, including better monitoring of substation state, metering, storage, and demand prediction.[34] These investments will likely also bring benefits in flood situations.

Financial mobilization to mitigate impacts on lower-income populations

In flood conditions, those who have the least often lose the most. In 2050, about 85 percent of the city's poor urban areas may expect to be exposed to flood risk in all flood return periods, compared with roughly 60 percent of the entire urban area.[35] For some lower-income professions such as dock working and agriculture, this is due to the need to be close to the water. These groups are more likely not only to be more exposed to flooding but also to struggle to recover. Poorer areas In Ho Chi Minh typically have lower-quality, unregulated housing that is damaged more severely in floods. Further, with highly limited financial reserves, insurance, or transferable skills, residents' ability to regain their livelihood after flooding will be diminished. Finally, the knock-on effects modeled exclude several that would face the poorest populations most—for example, increased disease risk, a disproportionate impact on small businesses from low grid reliability, and reliance on high-cost private water suppliers.

Raising funds for significant hardening measures will remain a challenge, but innovative models are emerging. In District 7, some main roads are raised each year using funding from a flood toll collected from users. Even when government and developers pay, investing to adapt can bring unexpected costs. In 2018, Huynh Tan Phat Street, a major thoroughfare, was raised 20 to 30 centimeters at a cost of about $20 million, covered by developers and the government.[36] The purpose is to avoid disruption and damage, yet it brings unintended consequences. Now that the road is higher, residents of adjoining homes need to cope with water pouring in or pay to upgrade their residences, which could cost $2,000 for a 90-square-meter house, around 35 percent of average annual income in HCMC.[37]

[33] Don H. Pickrell, "Estimates of rail transit construction costs," *Transportation Research Record*, 1985, Number 1006. One of the most thorough studies of unit construction costs, this research estimates the cost of over-ground train stations at approximately 2.5 times the cost of at-ground stations.

[34] Vietnam Electricity, "Ho Chi Minh City developing smart power grid," February 28, 2018.

[35] Mook Bangalore, Andrew Smith, and Ted Veldkamp, "Exposure to floods, climate change, and poverty in Vietnam," *Economics of Disasters and Climate Change*, April 2019, Volume 3, Number 1.

[36] "HCM City to start $22mil flood-prevention project", *Vietnam Net*, May 2017.

[37] Vietnam General Statistics Office via "HCMC posts highest average salary," *Vietnam Economic Times,* July 3, 2018.

Bristol could experience nonlinear flood risk that grows from a problem to a crisis by 2065

Bristol is facing a new flood risk. The River Avon, which runs through the city, has the second-largest tidal range in the world, yet it has not caused a major flood since 1968, when sea levels were lower and the city was smaller and less developed. Bristol recovered, built defenses, and grew to become a thriving top ten UK city by population. Yet the safety of those behind floodwalls hinges on the assumption of a static climate. Because of climate change, far more may now be at stake from the threat of a major flood. We collaborated with Bristol City Council to explore possible flooding scenarios for the city.

Bristol is an economically significant and fast-growing medium-sized European city. The eighth-largest city in the United Kingdom, it has a population of about 463,400 in the city boundary and more than one million in the greater urban area. Often considered a UK success story, Bristol has risen to become a politically important community and a desirable location to live. It has demonstrated rapid population growth of 11.7 percent since 2008 and received several accolades for its quality of life.[38] Having developed several clusters of high-skill services over the past 20 years, Bristol is considered one of the most economically productive cities in the United Kingdom outside London, and its GDP stands at about $40 billion.

Yet the city's bright future is at risk from a step change in flood risk, fueled by climate change. During very high tides, the Avon becomes "tide locked" and limits/restricts land drainage in the lower reaches of river catchment area. As a result, the city is vulnerable to combined tidal and pluvial floods, which are sensitive to both sea-level rise and precipitation increase.[39] Both are expected to climb with climate change. While Bristol is generally hilly and most of the urban area is far from the river, the most economically valuable areas of the city center and port regions are on comparatively low-lying land.

Unlike many small and medium-size cities, Bristol has invested in understanding this risk. It has undertaken a detailed review of how the scale of flooding in the city will change in the future under different climate scenarios. With the city's support, we have modeled the socioeconomic impacts of 200-year (0.5 percent probability) combined tidal and fluvial flood risk, for today and for 2065. This considers the flood defenses in existence today; some of these were built after the 1968 flood, and many assumed a static climate would exist for their lifetime.[40]

Analysis of flood risk in climate change reports often focuses on the usual suspects: high-risk, high-impact flood areas, typically large urban conurbations with a history of flood damage. These cities typically are comparatively prepared for floods of increasing severity. They usually have experienced a flood in generational history and have degrees, albeit often limited ones, of flood consideration in asset hardening, spatial policy, and societal preparation. Cities without the generational experience of floods may be more exposed on all three fronts. Approximately half of the world's urban dwellers reside in settlements with fewer than 500,000 inhabitants, and those with fewer than one million residents are the fastest-growing group of cities.[41] Despite their social significance, without holding the political and economic foci of their respective countries, they may lack the resources to prepare for or recover from floods.[42]

38 Bristol City Council.
39 E. Bevacqua et al, "Higher probability of compound flooding from precipitation and storm surge in Europe under anthropogenic climate change," *Science Advances*, September 2019, Volume 5, Number 9.
40 The Bristol City Council has kindly provided this data and its expert review for the purposes of our analysis in this study.
41 UN Department of Economic and Social Affairs, "68 percent of the world population projected to live in urban areas by 2050, says UN," press release, May 16, 2018.
42 John A. Cross, "Megacities and small towns: Different perspectives on hazard vulnerability," *Global Environmental Change Part B: Environmental Hazards*, June 2001, Volume 3, Number 2.

Bristol is not a usual suspect. Today its flood risk is modest. Yet our analysis identifies a step change in hazard, an exceptionally high level of exposure, and relatively large impact compared with the city's economy.

Knock-on effects of an extreme flood would increase by up to 22x by 2065 versus today

The consequences of a major flood today in Bristol would be small but are still material (City inundation-6). We find that the flood area would be relatively minor, with small overflows on the edges of the port area and isolated floods in the center of the city. Damage might amount to millions of dollars, and some travel disruption and workplace flooding would disrupt economic activity. Yet no major assets in the city would be destroyed, and life would likely return to normal in a period of days or a few weeks. Our model estimates that damage to the city's infrastructure could amount to $10 million to $25 million, real estate damage to $15 million to $20 million, and knock-on effects to $20 million to $150 million.

In contrast, by 2065, an extreme flood event could be devastating (City inundation-7 and -8). Water would exceed the city's flood defenses at multiple locations, hitting some of its most expensive real estate, damaging arterial transportation infrastructure, and destroying sensitive critical energy assets. The flood defenses are inadequate in the face of rising water levels. Critically, we find that the city's most valuable energy, transportation, and commercial assets are in the areas of highest flood risk. Our model estimates that damages to the city's infrastructure could amount to between $180 million and $390 million, with ~60 percent from damage from energy infrastructure and ~40 percent from damage to transport infrastructure.

Many energy assets are positioned immediately next to the river or sea. Our model suggests that a flood could cause damage to a major power plant, inundate a major substation that feeds an area covering approximately 20 to 30 percent of Bristol, cut off the main train station from all access, and flood the port, including one of the largest car-storage areas in the United Kingdom, with a capacity of 90,000 new automobiles. It may also cause $160 million to $240 million of property damage, particularly to high-value riverfront homes and large swaths of the central business district, as well as $10 million to $130 million of lost infrastructure operating revenues, largely dependent on whether and for how long the power station is disrupted.

A flood of this magnitude would also create cascading economic and social knock-on effects, magnifying the consequences of infrastructure failure. About half of these effects would be associated with transportation failures, including lost economic benefits of the port, delays to road journeys, lost working hours from rail closures, and damage to the extensive freight storage at Avonmouth. Roughly a quarter of the effects would be associated with energy failures, specifically the loss of working hours if certain parts of the city lose electricity, and the remaining quarter with direct inundation of buildings. Smaller businesses are likely to be hit hardest, and we estimate that 25 to 100 of Bristol's smaller enterprises may go out of business, permanently damaging the economy. Other services not examined here may also be disrupted, such as waste collection; flooding at waste centers near Avonmouth as well as city center traffic disruption may cause refuse to pile up on the streets. Overall, considering economic growth, knock-on effects could total $500 million to $2.8 billion, and disruptions could last weeks or months.

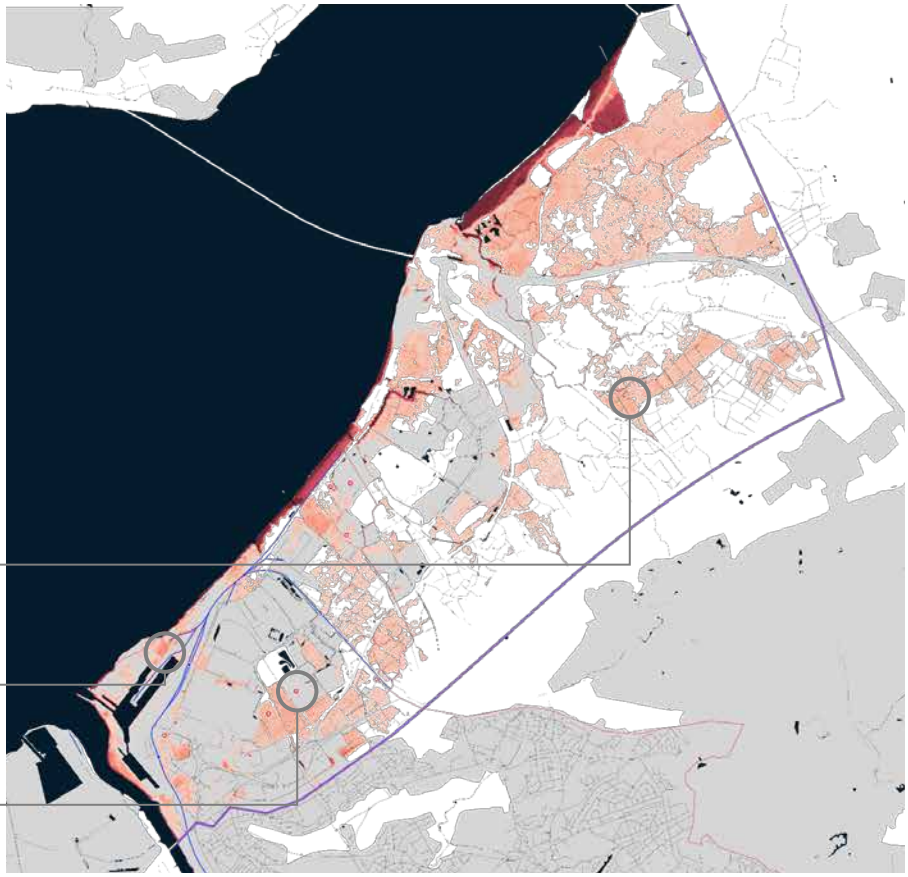
Today, Bristol has minimal risk of flooding from a 200-year event, being largely protected by its existing flood defenses.

200-year flood today

- Power station
- Substation (high voltage)
- Substation (low voltage)
- Railway station
- Railway
- Urban areas
- Modeled areas (port)

Inundation depth (m)
0 3+

Avonmouth port

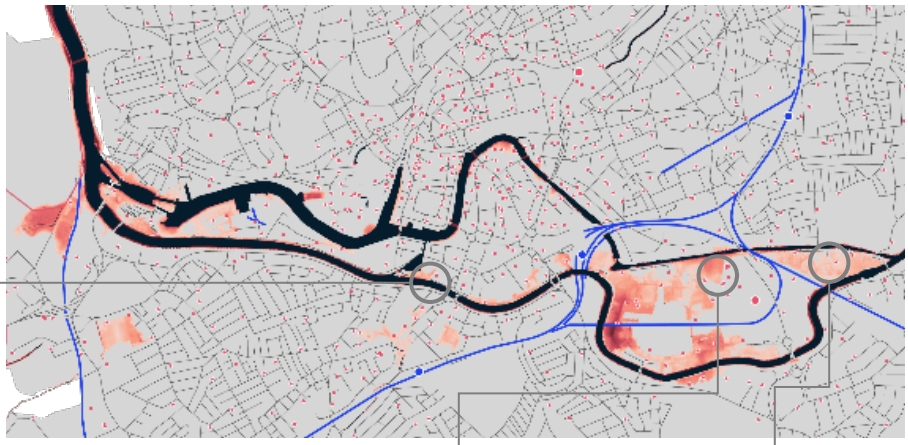


Low-lying, primarily rural inland areas may flood

Harbor may experience flooding; overflow onto industrial areas limited

Limited flooding of some small power assets is unlikely to be sufficient to cause major damage

City center



Minor overflows in small areas at very low depths

Areas of light damage in industrial areas surrounding main train station; low depths

Some disruption to roads likely; traffic will slow on many, and a few may be impassable

Note: Not to scale.
Source: Bristol City Council; publicly available infrastructure databases; McKinsey Global Institute analysis

In 2065, a 200-year flood may not damage a large area of Bristol, but many critical infrastructure assets and high-value real estate in exposed locations could be inundated.

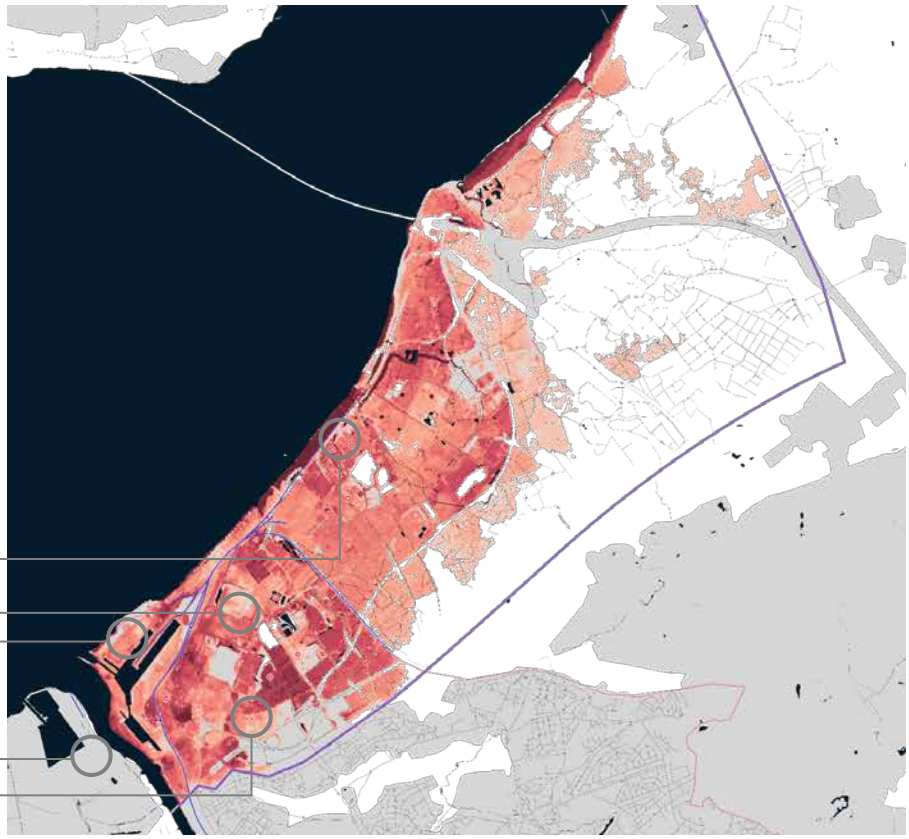
Based on RCP 8.5

200-year flood in 2065

- Power station
- Substation (high voltage)
- Substation (low voltage)
- Railway station
- Railway
- Urban areas
- Modeled areas (port)

Inundation depth (m)
0 3+

Avonmouth port



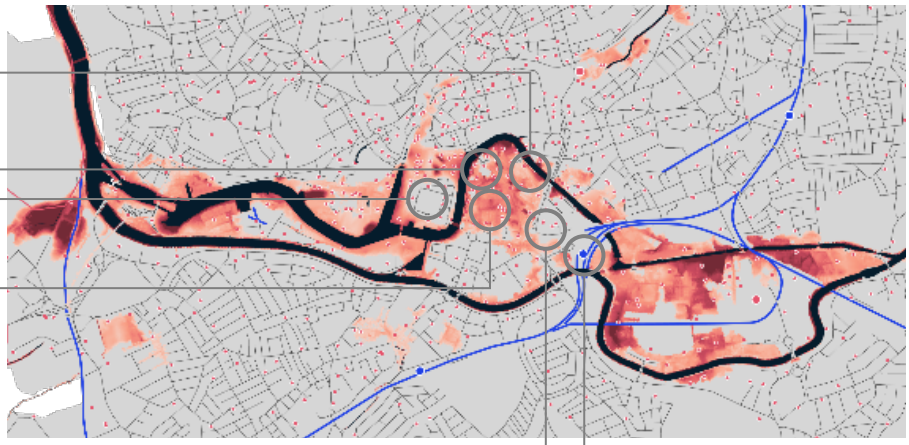
Major gas power plant flooded

Main port area inundated

One of the United Kingdom's largest new-car storage points (~90,000 cars) flooded

Major substation that powers ~20–30% of Bristol flooded

City center



~1/3 of the central road network flooded, including underpass connecting Bristol with main motorway to London

Cultural district of Kings Street and Harbourside flooded

Central business district bears brunt of flooding with ~50% underwater

Very high-value enterprise zone of commercial real estate (HQs of several major national corporations) saved from flooding but largely inaccessible to workers

Main train station not flooded but largely inaccessible; most rail lines flood, preventing ~30,000 trips per day, many to London

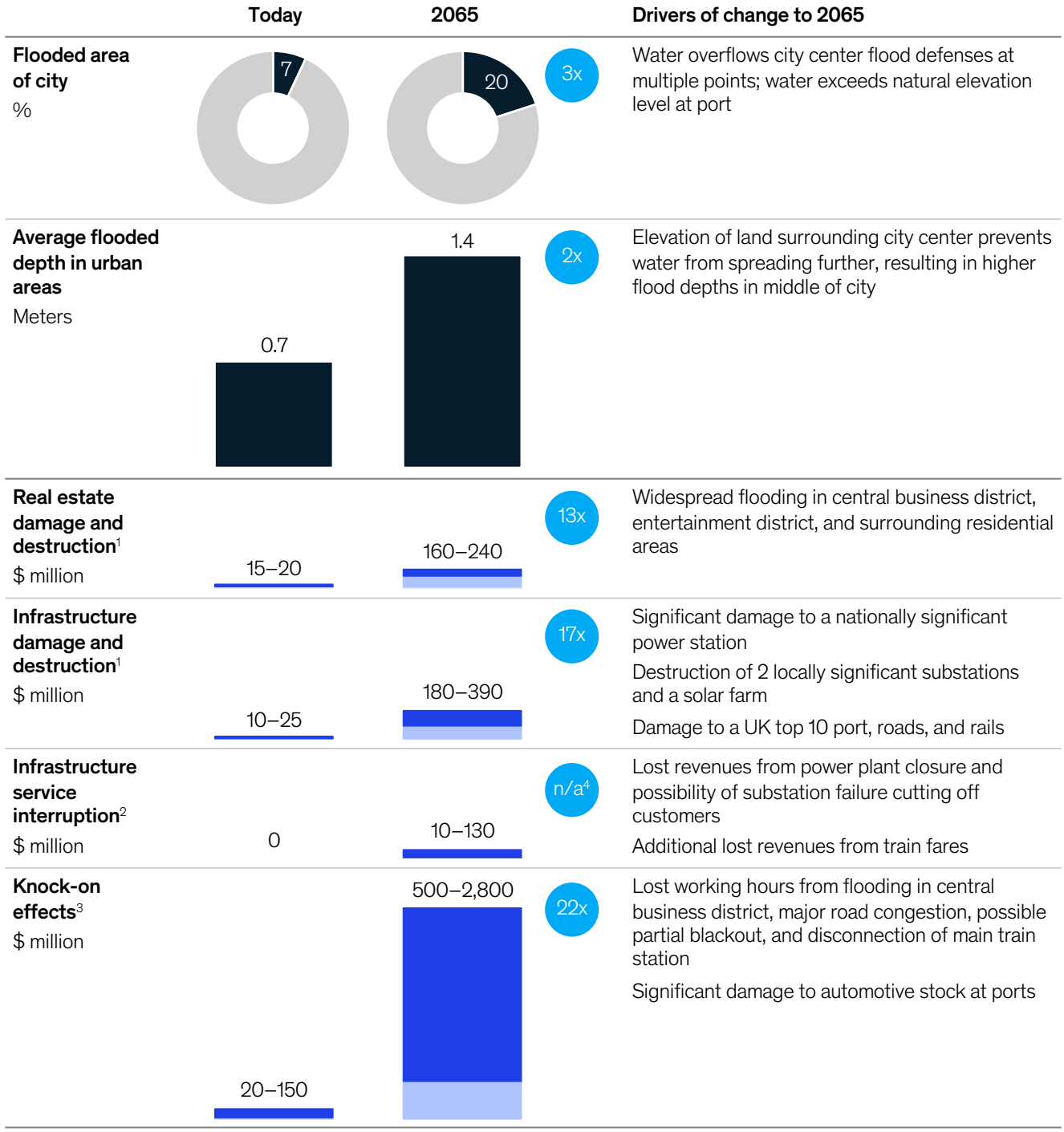
Note: See the Technical Appendix of the full report for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multimodel ensemble. Heat data bias corrected. Not to scale.
Source: Bristol City Council; publicly available infrastructure databases; McKinsey Global Institute analysis

By 2065, a 200-year flood in Bristol could be twice as extensive compared to today but produce 18 times more infrastructure damage and 30 times more knock-on effects.

Based on RCP 8.5

200-year (0.5% per year probability) flood effects

x Ratio today/2065 | High | Low


Today
2065
Drivers of change to 2065
Flooded area of city
%
7
20
3x
Water overflows city center flood defenses at multiple points; water exceeds natural elevation level at port
Average flooded depth in urban areas
Meters
0.7
1.4
2x
Elevation of land surrounding city center prevents water from spreading further, resulting in higher flood depths in middle of city
Real estate damage and destruction[1]
$ million
15–20
160–240
13x
Widespread flooding in central business district, entertainment district, and surrounding residential areas
Infrastructure damage and destruction[1]
$ million
10–25
180–390
17x
Significant damage to a nationally significant power station
Destruction of 2 locally significant substations and a solar farm
Damage to a UK top 10 port, roads, and rails
Infrastructure service interruption[2]
$ million
0
10–130
n/a[4]
Lost revenues from power plant closure and possibility of substation failure cutting off customers
Additional lost revenues from train fares
Knock-on effects[3]
$ million
20–150
500–2,800
22x
Lost working hours from flooding in central business district, major road congestion, possible partial blackout, and disconnection of main train station
Significant damage to automotive stock at ports

1. Repair and replacement costs.
2. Costs from lost infrastructure revenue.
3. Value of wider societal consequences of flooding, with a focus on those attributable to infrastructure failure; covers issues of lost customer surplus, GDP, and capital stock. Adjusted for forecast economic growth.
4. Minimal energy losses in 2018 create a distorted ratio if calculated.

Note: See the Technical Appendix of the full report for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multimodel ensemble. Heat data bias corrected.

Source: Bristol City Council; BTE; CATDAT disaster database; CAPRA; ECLAC; HAZUS; Western Power Distribution; historical insurance data; review of critical points of failure in infrastructure assets by chartered engineering consultants; McKinsey Global Institute analysis

The story of Bristol is one of severe floods delivering disproportionately greater impacts. Typically, smaller floods cause less damage to infrastructure assets as thresholds are not passed or flooding is low depth (and thus less damaging). Redundancy avoids cascading failures, and few inter-sector dependencies manifest. Cleanup and repair are faster. Bigger floods, in contrast, destroy some infrastructure assets and cause more infrastructure to be damaged more severely. Repeated failure overcomes system redundancy, causing failures over a wider area. Interdependencies push outages into other sectors, for example as power cuts slow transportation systems. Certain effects (such as company bankruptcy and permanent population relocation) occur only above certain thresholds. After an extensive and severe flood, cleanup and repair are slower. These factors compound to magnify one another, hitting urban areas harder.

Simulations show that Bristol has amplified this relationship through high infrastructure exposure. Flood defenses are close to their tipping points, and assets are positioned directly behind them in the highest-risk areas. The city could experience an even larger impact than models indicate. Because of Bristol's size, the relative economic impact as a percentage of GDP is comparable with the fallout of much larger disasters in bigger cities. Today, the flood impact would be essentially zero percent of gross value added. Yet in 2065, the possible flood impact translates to 2 to 9 percent of the GVA in the city, comparable to Hurricane Sandy's impact on New York (about 4 percent) and Hurricane Harvey's impact on Texas (about 8 percent).[43] Operationally, the city may also be at a disadvantage compared with larger and more experienced peers. For example, Bristol may have less financial capacity to recover, particularly if it already faces challenges to compete with larger cities into the next century.[44] From a global perspective, differences in preparation—cultural, political, or physical—may be even more pronounced in developing cities exposed to significant risk for the first time, such as Luanda, Angola, and Mogadishu, Somalia.[45]

Nationally, the United Kingdom's relatively small size means that urban flooding often strikes multiple cities when a major storm hits the country. The durations observed in the 2065 scenario may be even more protracted if ten to 20 major urban areas suffer flood impacts concurrently, because finite national resources will be spread thinly across the country.

[43] Statista, Texas - real GDP 2000-2018 Published by Erin Duffin, May 10, 2019; National Oceanic and Atmospheric Administration, Costliest U.S. tropical cyclones tables updated; Statista, New York metro area - GDP 2001-2018, Published by Erin Duffin, Dec 18, 2019.

[44] *Superstars: The dynamics of firms, sectors, and cities leading the global economy,* McKinsey Global Institute, October 2018.

[45] Susan Hanson et al., "A global ranking of port cities with high exposure to climate extremes," *Climatic Change*, January 2011, Volume 104, Number 1.

As a smaller city, Bristol provides an example of proactively understanding risk that others could learn from

Unlike many small and medium-size cities, Bristol has invested in understanding this risk. It has undertaken a detailed review of how the scale of flooding in the city will change in the future under different climate scenarios. This improved understanding of the risks is an example that other cities could learn from.

However, adaptation is unlikely to be straightforward. It is difficult to imagine Bristol's infrastructure assets being in a position more exposed to the city's flood risk. Yet the center of the city, formed in the 1400s, cannot be shifted overnight, nor would its leafy reputation be the same today if the city had not oriented the growth of the past 20 years to harness its existing Edwardian and Victorian architecture. Unlike in Ho Chi Minh City, most of the infrastructure the city plans to have in place in 2065 has already been built. In the short term, Bristol's hands are likely largely tied, and hard adaptation may be the most viable short-term solution. In the medium term, however, Bristol may be able to act to improve resilience through measures such as investing in sustainable urban drainage that may reduce the depth and duration of an extreme flood event.

Bristol is already taking a proactive approach to adaptation. A $130 million floodwall for the defense of Avonmouth was planned to begin in late 2019.[46] While a significant step, it will not eliminate the threat to the port, nor will it touch upon the city center's risk. As in many smaller cities wrestling with new flood risks, some suggested measures—such as an Avon Barrier to protect the center of the city—may not garner the same attention from national investment sources that has funded adaptation in larger cities, such as London's Thames Barrier, currently undergoing an upgrade to meet protection levels for 2100.[47] The city is still scoping out a range of options to protect the city. As an outside-in estimate, based on scaling costs to build the Thames Barrier in 1982, plus additional localized measures that might be needed, protecting the city to 2065 may cost $250 million to $500 million (roughly 0.5–1.5 percent of Bristol's GVA). However, the actual costs will largely depend on the final approach.

Smaller cities like Bristol may need to work harder to raise awareness of the value at stake and to come up with innovative low-cost designs and new approaches to funding. Evidence globally suggests that, while there is a correlation between level of flood protection and GDP per capita, political prioritization can create exceptions. For example, while richer cities like Amsterdam, London, Rotterdam, and Tokyo are protected to better than a 1,000-year event, New York, despite having a higher GDP per capita of any of those cities, is protected to about a 100-year event. Due to political prioritization, Shanghai has protection estimated to be similar to that of London, even though its GDP per capita is less than half that of Bristol.[48]

Bristol has gotten ahead of the game by improving its own understanding of risk. Many other small cities are at risk of entering unawares into a new climatic band for which they and their urban areas are ill prepared. While global flood risk is concentrated in major coastal metropolises, a long tail of other cities may be equally exposed, less prepared, and less likely to bounce back.

46 BBC News, "Avonmouth sea wall flood defence 'should start in summer,'" March 11, 2019.
47 Thames Estuary 2100, UK Government, https://www.gov.uk/government/publications/thames-estuary-2100-te2100
48 Susan Hanson et al., "A global ranking of port cities with high exposure to climate extremes," *Climatic Change*, January 2011, Volume 104, Number 1.

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